*Status and Plans for the PEGASUS Toroidal Experiment**

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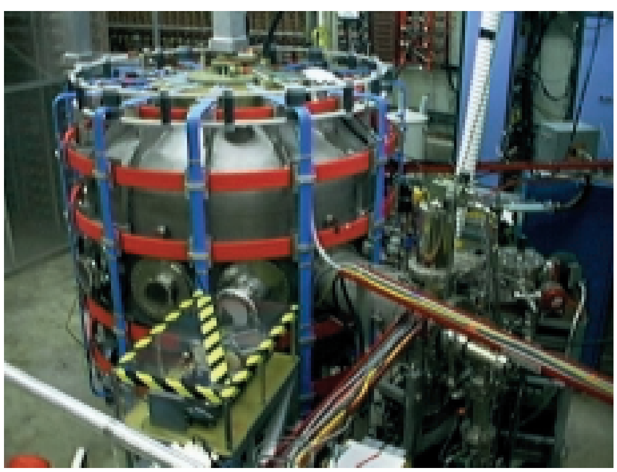
An extremely low-aspect ratio facility exploring quasi-spherical high-pressure plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

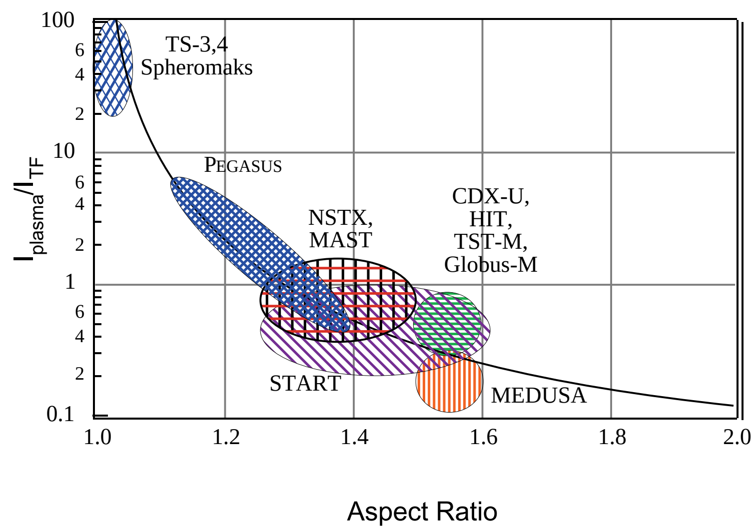
- Explore the extreme limit of low-aspect ratio physics



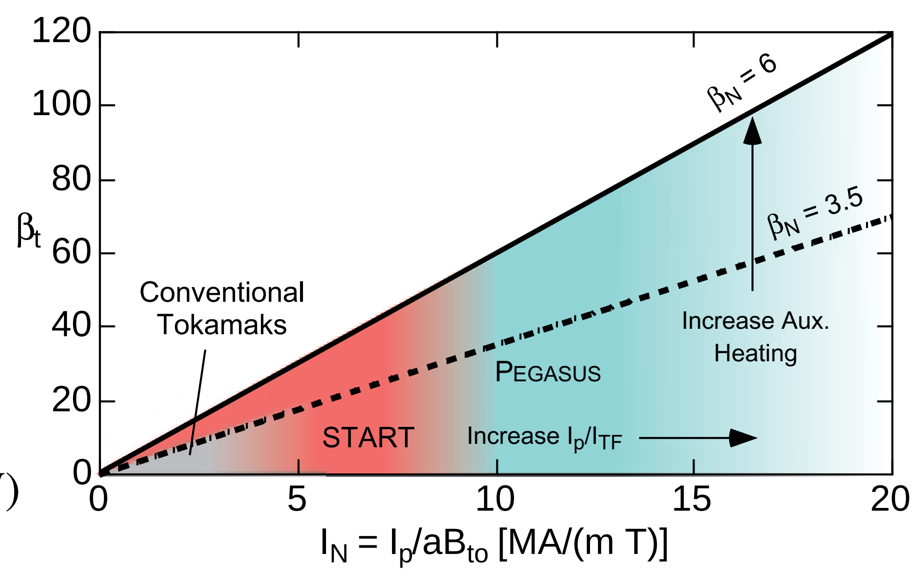
*Supported by U.S. DoE grant No. DE-FG02-96ER54375

Role of the PEGASUS Experiment

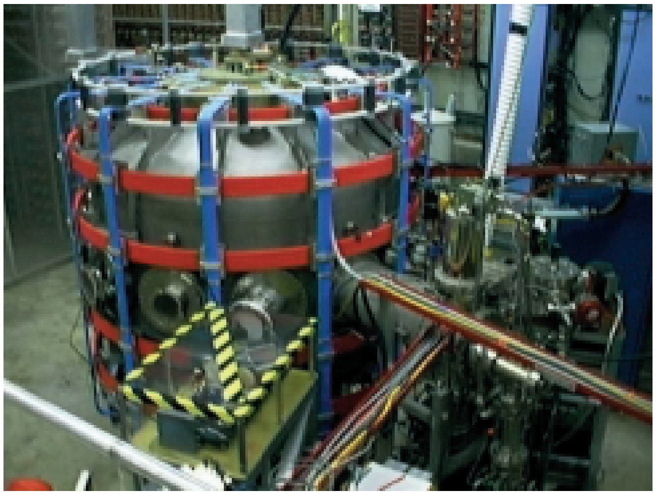
- **Physics of A ≈ 1 plasmas as an Alternate Concept (low q)**
  - Extreme toroidicity ($A \rightarrow 1$)
  - Very high TF utilization $(I_P/I_{TF}) > 3$
  - Stability at very low TF ($\beta \approx 1$)
  - Relaxation stability at tokamak/spheromak boundary
  - RF heating and CD schemes (HHFW, EBW)
  - Trade-offs: CD, recirculating power, and $A \approx 1$, low-TF operation

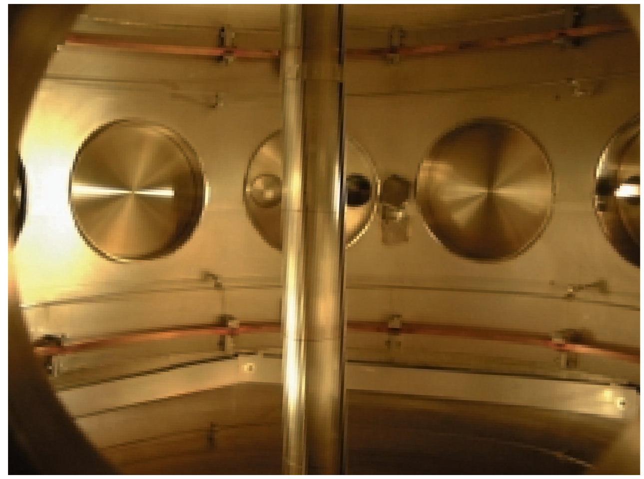


- **Contribute to development of the ST (high q)**
  - Stability limits for $A \rightarrow 1$ (vs. I_p/I_{TF}, q_ψ, N_e, β_t, β_{pol}, κ, A, etc.)
  - β limit dependencies
  - Access high β_t at extreme I_N w/o conducting shell
  - Confinement $A < 1.3$
  - New startup schemes (e.g., plasma gun, EBW)



A → 1 Operation via High-Stress Solenoid





PEGASUS Operational Parameters

Parameter	Present	Full
A	1.16 - 1.3	1.1 - 2.0
R	0.2 - 0.3 m	0.2 - 0.45 m
I_p	0.1 MA	0.1 - 0.3 MA
B_t	≤ 0.1 T	≤ 0.15 T
κ	~ 1.5 - 3.0	~ 1.5 - 3.7
Δt_{pulse}	3 - 8 msec	30 - 60 msec
β_t	0.03 - 0.2	$O(1)$
β_N	1 - 5	> 5
I_N	~ 2 - 6	> 10
Heating and Sustainment	Inductive*	Inductive*+ RFCD (HHFW, EBW), Plasma Guns

* NHMFL: $B_{solenoid}$ = 10 - 14 T

- Phased program plan matches resources
  - I. Operation w/high-field solenoid & conducting vessel (limited OH)
  - II. Full OH operation; shape & q-boundaries as A → 1
  - III. Auxiliary heated; β_t limits as A → 1
  - IV. Stability and confinement; tokamak/spheromak overlap

PEGASUS Contributes to FESAC Goals and Objectives

Goal	5-Year Objective	PEGASUS Contribution
1. Advance fundamental understanding of plasma	Turbulence and transport	Confinement scaling as $A \rightarrow 1$ Microturbulence studies (with UCLA)
	Macroscopic stability	Study stability as $A \rightarrow 1$: q-limits, shaping, high-beta boundary, tokamak/spheromak overla
	Wave-particle interactions	HHFW, EBe, EBW heating and CD
	Advance forefront of non-fusion plasma science	Reconnection physics MHD stability
2. Resolve outstanding scientific issues and establish reduced-cost paths	Make preliminary determination of attractiveness of ST	High-beta stability as a function of A, κ, q Confinement scaling q-limits CD needs vs B_T
	Resolve key issues for a broad spectrum of configurations	Startup and CD schemes Tokamak/spheromak overlap
3. Advance understanding and innovation in high-performance plasmas	Assess profile control methods	Study CD techniques Also support this goal in the general sense of studying ST path

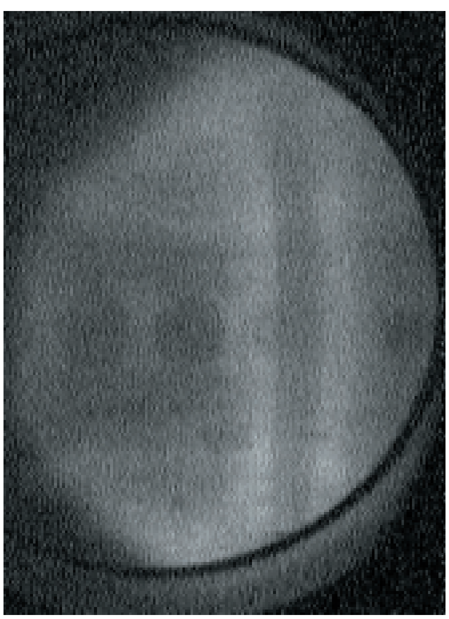
First Campaign: OH Plasma Formation

- **Successful high-stress solenoid operation**

- **Startup at low B_t in presence of conducting walls**
  - Induced wall currents reasonably understood
  - Startup achieved at $B_{to} \sim 0.05$ T

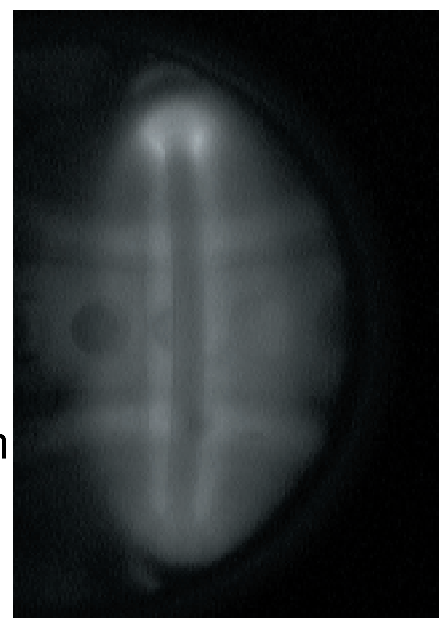
- **Short-pulse startup plasmas show low-A characteristics**
  - *High β_t, β_N* — $\beta_t \sim 20\%$, $\beta_N \sim 5$
  - *High TF utilization factor* — $I_p/I_{TF} \sim 1$
  - *High normalized current* — $I_N \sim 6$
  - *High density* — $n_e \sim n_{GW}$
  - *IRE's, tearing modes*

- **Accessed a variety of plasma geometries**



R = 0.34 m
a = 0.29 m
A = 1.17
$\kappa \approx 1.8$

R = 0.2 m
a = 0.15 m
A = 1.3
$\kappa > 3$



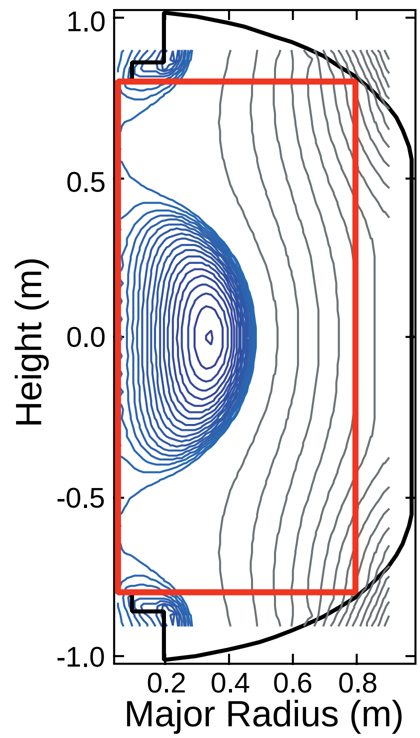
(Geometric Plasma Properties Estimated from Visible Images)

First Results Promise Interesting Full-Power Operation

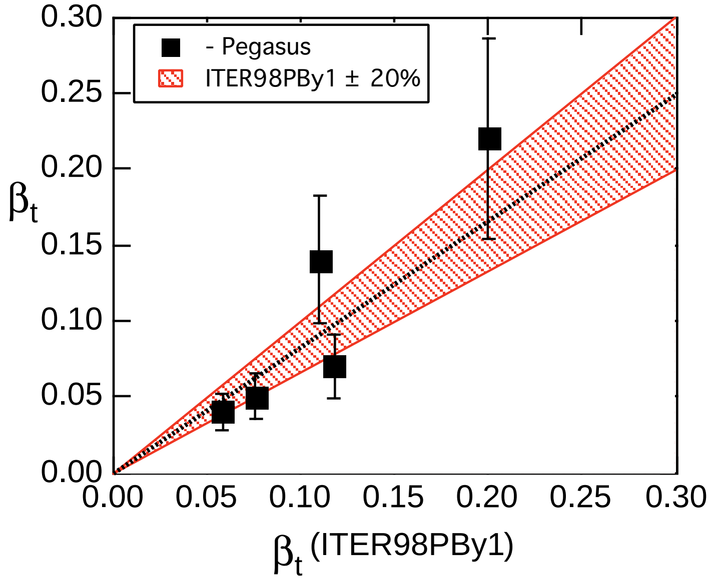
- **Moderately high β_t accessed in startup ohmic plasmas**
  - Reconstruction via 6-8 Bp coils, 4-6 flux loops, + camera image

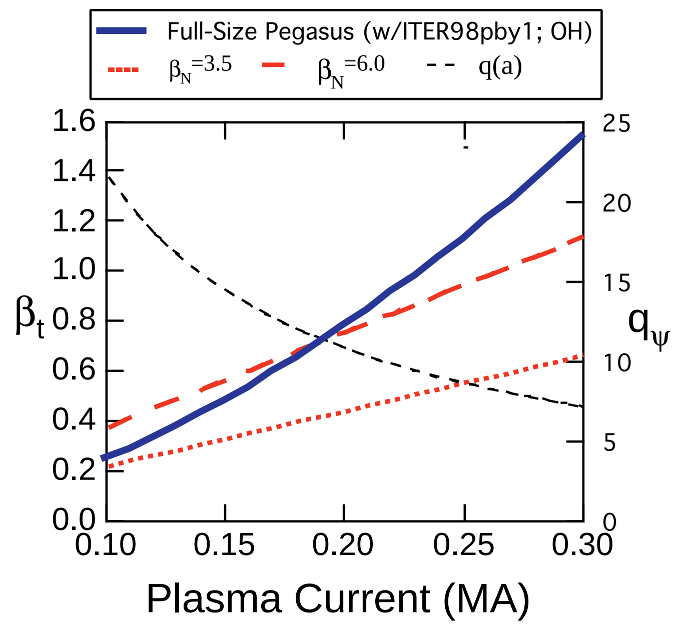
Shot 4699

R	= 0.27 m	I_P	= 0.065 MA
a	= 0.22 m	β_{pol}	= 0.6
A	= 1.22	ℓ_i	= 0.35
κ	= 2.1	β_t	≈ 0.22
I_{TF}	= 0.09 MA	β_N	= 4.9
q_a	≈ 7	q_0	≈ 1.5



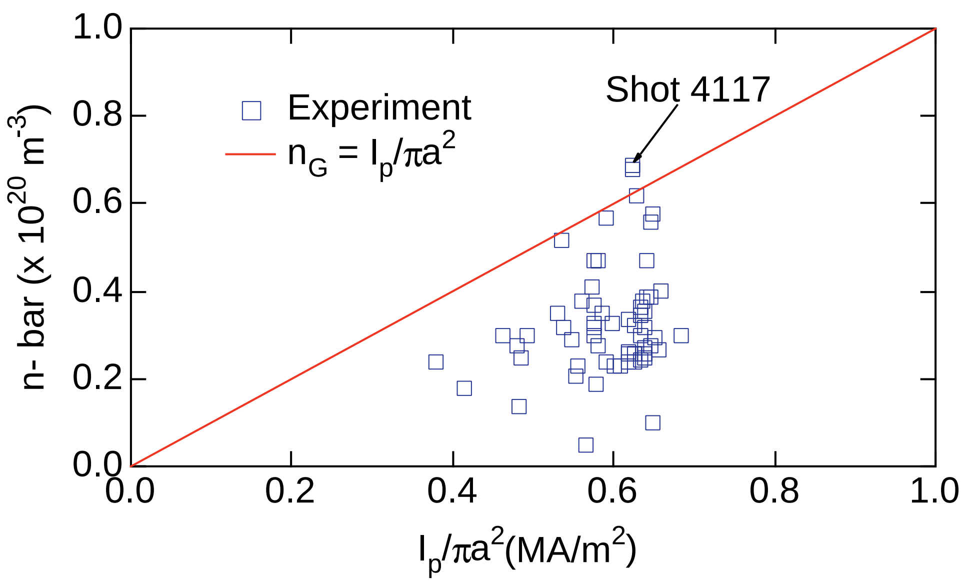
- **Estimates of β_t consistent with START scaling**
  - β_t from magnetic equilibrium reconstruction
  - High β_t accessible at full OH power, higher T_e with aux heating



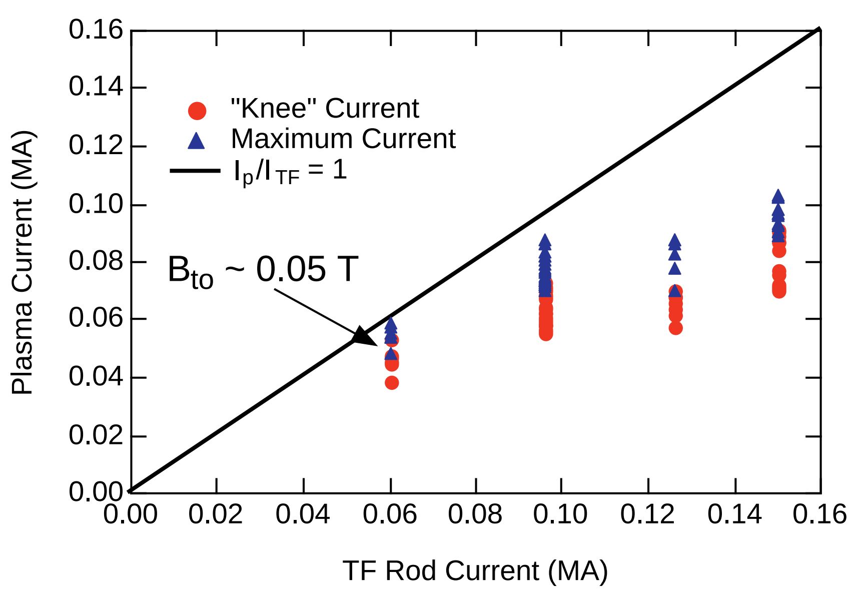


High Density and Low-TF Operation Achieved

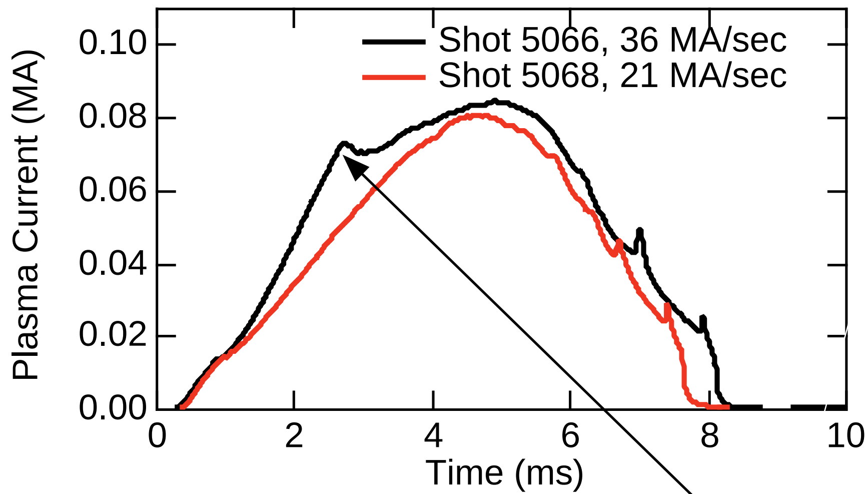
- **Density Approaches the Greenwald Limit**



- **$I_p/I_{TF} \rightarrow 1$ at lowest TF settings**
  - Tearing modes limit I_p ramp rate $\rightarrow$ high I_p/I_{TF} only at low TF
  - Present limits on I_p/I_{TF}: ramp rate and pulse length $\Leftrightarrow$ OH power supply

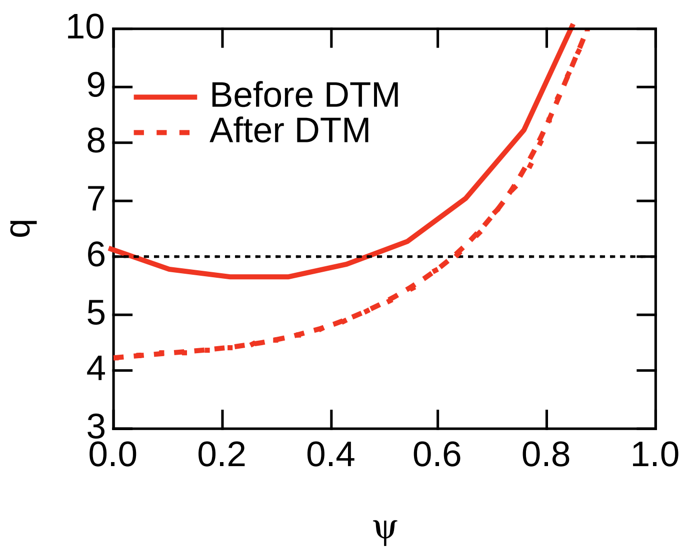


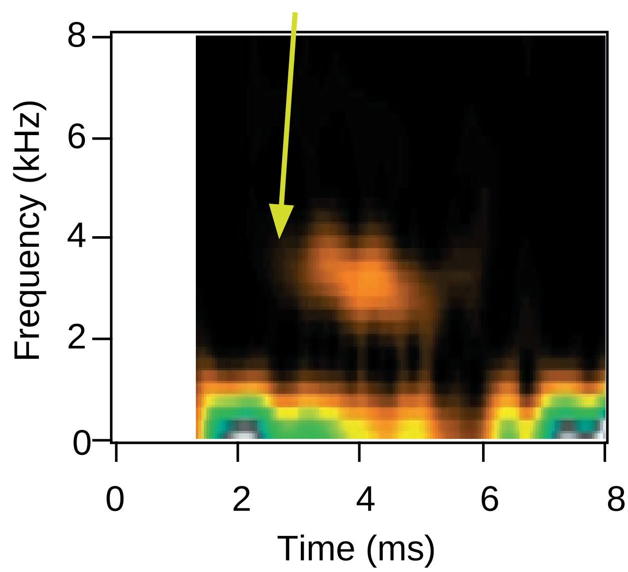
Double Tearing Modes Limit Plasma Current Ramp Rate



Similar events on MEDUSA identified as DTM's with internal j(r) measurements

Shot 5066: m=2 mode after “knee” in plasma current





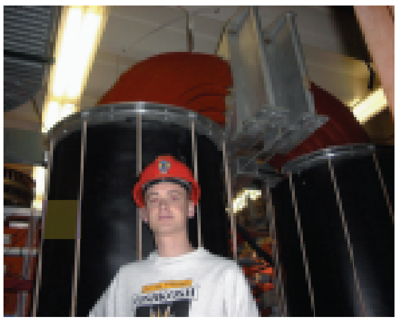
q profile flattens and current penetrates into the core after the DTM

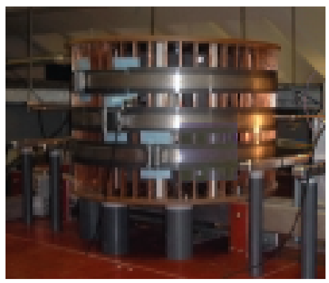
m = 2 activity observed on Mirnovs and interferometer

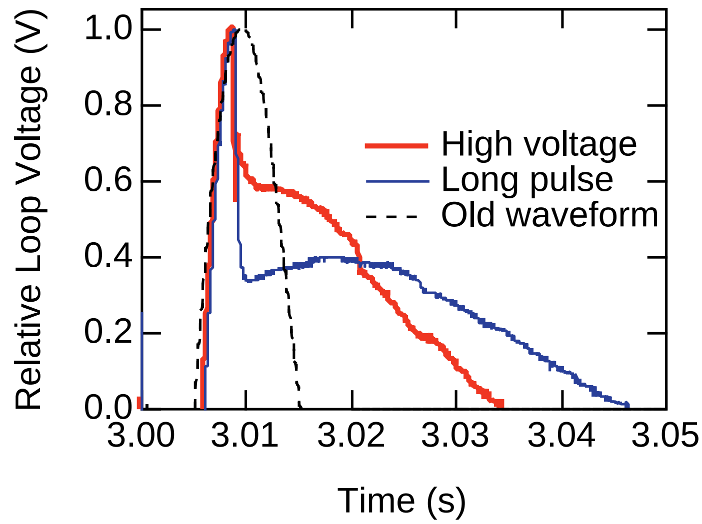
- I_p ramps up to 30 MA/sec are stable

Near-Term: High-Power OH Operation

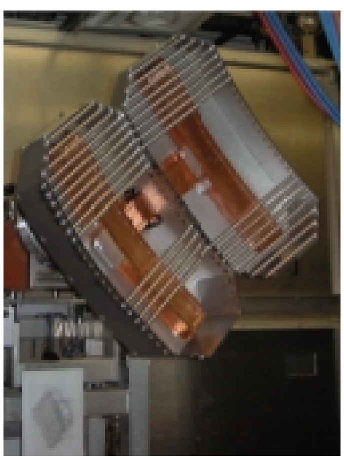
- **OH power supply completed:**
  - Step-down transformer + inductors for impedance matching
  - Longer pulse, more flexible waveform control







- **RF heating system & internal hardware due in Spring opening**



  - 1-2 MW HHFW: 0.5 MW tested
  - First antenna fabricated

  - Enhance core armor and limiters
  - Expand magnetics diagnostics

  - Test plasma gun

- **FY2000 plans: Low-q/low-TF stability studies @ full OH power**
  - Limits of I_p/I_{TF} operation as $A \rightarrow 1$
  - Low-q limits @ $A < 1.3$
  - High β_t OH plasma studies
  - Loading/coupling tests for HHFW

PEGASUS Toroidal Experiment
University of Wisconsin-Madison

Two-Year Research Program

- **FY2001: Stability limits and confinement and at low-A**

Physics Goals:

- *MHD stability limits: shaping, profiles, configuration effects*
- *Initial HHFW heating and β_t limit studies with DC TF*
- *Confinement evaluation*

Facility Development:

- *Diagnostics: DNB, Thomson scattering, 2-D SXR imaging*
- *Divertor power supply*
- *EBW heating design*
- *New TF power supply for fast ramping*

- **FY2002: High β_t exploration at high and low edge-q**

Physics Goals:

- *Continued MHD stability limits*
- *Minimal B_t to stabilize spheromak-like relaxation*
- *Startup and sustainment: plasma guns and EBW*
- *CD needs for as $A \rightarrow 1$ ST*

Facility Development:

- *Develop low-inductance TF system*
- *Complete first EBW heating system*
- *Begin multichannel IF system for turbulence characterization (UCLA)*

PEGASUS Budget Overview

- PEGASUS budget is chronically under severe constraint
  - Manpower at a minimum (e.g., 0.25 FTE for RF engineering)
  - Loss of most equipment in most projected cases; personnel loss in most severe case
  - Decreased ability to achieve goals in timely manner w/o increment in FY01 and FY02

Case	1 *FY00* *funded*	2 *FY01* *Proposal*	3 *FY01* *FY00 - 6%*	4 *FY02* *Proposal*	5 *FY02* *FY01-10%*	6 *FY02* *FY01 flat*	7 *FY02* *FY01+10%*	
Personnel	360	376	371	391	343	382	382	($K)
Fringes	87	91	90	95	92	92	92	($K)
Travel	17	15	15	15	10	15	15	($K)
Operations	65	63	60	62	46	57	58	($K)
Overhead	233	240	236	247	216	240	241	($K)
Equipment	75	83	15	77	0	0	77	($K)
Total ($K)	837	868	787	887	708	787	865	($K)

Personnel = 5.6 FTE: Scientists, Engineer, Technician, Faculty, Secretary
Students: Graduate (5) and Undergraduate (8)

Operations = Materials, Supplies, Shops, Diagnostics, Computers & DAS, Publications, etc.

Projected Budgets are Severely Constraining

- **Case 3: FY01 = FY00 - 6%**
  - Reductions: (Equipment = -\$68K) Δ-Prop = -\$86K

Power supply spares	Reduced RF support
Divertor hardware	µwave interferometer (UCLA)
Plasma guns	EFi repairs

- **Case 6: FY02 = FY01 flat (= FY00 - 6%)**
  - Reductions: (Equipment = -\$77K) Δ-Prop = -\$100K

Thomson scatt	EBe/EBW
Divertor hardware	µwave interferometer (UCLA)
Plasma guns	SXR array

  - <u>Goals affected</u>:
    - Divertor operation curtailed ⇒ stability & confinement
    - Internal measurements ⇒ MHD stability studies weakened
    - Startup and CD developments eliminated

- **Case 5: FY02 = FY01 - 10%**
  - Reduction: (Equip = -\$77K; 6 stdts - 2 G, 4 UG) Δ-Prop = -\$179K

Thomson scatt	EBe/EBW
Power supply support	DAS

  - <u>Goals affected</u>: most 5-year FESAC objectives weakened
    - RF heating support reduced; EFi marginal ⇒ less reliability
    - No fast TF ramp capability: spheromak-tokamak overlap
    - Startup and CD developments eliminated

- **Case 7: FY02 = FY01 + 10%** Δ-Prop = -\$22K
  - Single-point Thomson scattering lost; Other activities delayed ~ 1 year

Budget Limitations Reduce Contributions to FESAC Goals

Goal	5-Year Objective	Pegasus Contribution
1. Advance fundamental understanding of plasma	Turbulence and transport	~~Confinement scaling as A → 1~~ ~~Microturbulence studies (with UCLA)~~
	Macroscopic stability	Study stability as A → 1: q-limits, shaping, high-beta boundary, ~~tokamak/spheromak overlap~~
	Wave-particle interactions	HHFW, ~~EBW heating and CD~~
	Advance forefront of non-fusion plasma science	~~Reconnection physics~~ MHD stability
2. Resolve outstanding scientific issues and establish reduced-cost paths	Make preliminary determination of attractiveness of ST	High-beta stability as a function of A, κ, q ~~Confinement scaling~~ q-limits ~~CD needs vs B_T~~
	Resolve key issues for a broad spectrum of configurations	~~Startup and CD schemes~~ ~~Tokamak/spheromak overlap~~
3. Advance understanding and innovation in high-performance plasmas	Assess profile control methods	~~Study CD techniques~~ ~~Also support this goal in the general sense of studying ST path~~

Increments in FY01 & FY02 Needed for PEGASUS Project

- Increment requests for Pegasus program in FY01 & FY02
  - Scenario I:
    Recover projected major cuts in equipment and operation;
    Timely acquisition of single-point Thomson Scattering (TS) laser;
    TS and RF manpower
    - *Keep project on track and capable of producing timely results*
  - Scenario II:
    Recover projected major cuts in equipment and operation
    - *Minimal to avoid cutbacks to subcritical program*

Costs ($K) above FY01 & FY02 Guidances

	Scenario I		Scenario II		
Item	**FY01**	**FY02**	**FY01**	**FY02**	
Divertor power supply	15		15		
Thomson scattering laser	85		20	65	
EBe, EBW tests	10	5	10	5	
Ohmic power supply	5	5	5	5	
HHFW support		5		5	
Operations; materials & supplies	15	10	15	5	
Personnel - Post-doc	70	70			
Personnel - RF scientist (1/4 FTE)	35	35			
Total =	**235**	**130**	**65**	**85**	**($K)**

Summary

An extremely low-aspect-ratio toroidal (ELART) facility exploring quasi-spherical high-β plasmas with the goal of minimizing the central column while maintaining good confinement and stability.

Support Development of the Spherical Tokamak and Contribute to Alternate Concept physics understanding

- Primary goal is to explore the $A \rightarrow 1$ regime
  - *Tokamak/Spheromak Overlap: How close can $A \rightarrow 1$ and maintain good stability and confinement?*
  - *Geometry (A, κ, separatrix) and current profile (ℓ_i, q_o, q_ψ) influence on the stability limits?*
  - *Tradeoffs between $A \approx 1$ and current drive requirements?*

- Phased program of increasing capability
  - *OH operation; shape & q-boundaries as $A \rightarrow 1$*
  - *Auxiliary heated; β_t limits as $A \rightarrow 1$*
  - *Stability and confinement; tokamak/spheromak overlap*
  - *Startup and CD techiques to eliminate core solenoid*

- Program contributions strongly dependent on budget increments

PEGASUS has Benefited Greatly from Contributions from Members of the Fusion Science Community

- **Collaborations**

NHMFL:	Solenoid design, fab., tests
General Atomics	Stress Analyses; VV construction; Power Systems; Theory; Future expts.
PPPL:	RF; Power Engr.; DNB assistance
UCLA:	µwave interferometer
MST:	Engineering; diagnostics; e-gun j sources

- **Contributions**

NHMFL	High-stress Magnets
General Atomics	Vacuum Vessel, Iron core
PPPL	Capacitors; diagnostics; CAMAC
LANL	Capacitors; Ignitrons, RF systems
MST	Ross diodes; iron core; caps, etc.
HSX	EF cap bank
LLNL	Caps; DNB power system
ORNL	Thomson scattering
Westinghouse	High-E cap bank
UW SC Lab:	TF hex conductor